DØ note 5465-CONF

Measurement of the $t\bar{t}$ Production Cross Section in the Lepton+Track Channel with 1 fb^{-1} of Run II Data

DØ Collaboration

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The $t\bar{t}$ to dilepton cross-section was measured in the lepton+track channel, where only one lepton (either an electron or a muon) was identified in the detector and the second lepton is identified as an isolated track. This analysis is primarily intended to be combined with the fully identified dilepton channels [1], and thus a dilepton veto was used that rejects events where both leptons were identified. The Z boson background is reduced by requiring at least one jet to be identified as a b quark jet. This analysis is based on the Run IIa dataset of approximately 1 fb^{-1}. The measured value of the $t\bar{t}$ cross section is

$$\sigma(\mathrm{M_{top}} = 170.9\mathrm{GeV}) = 5.2^{+1.6}_{-1.4}(stat)^{+0.9}_{-0.8}(syst) \pm 0.3(lumi)$$

I. INTRODUCTION

The theoretical cross section for top quark pair production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV is calculated by Cacciari et al. to be $6.7^{+0.7}_{-0.9}$ pb [2] and Kidonakis and Vogt [3] to be 6.8 ± 0.6 at next to leading order (NLO) for a top quark mass of 175 GeV. According to the Standard Model, the top quark decays almost exclusively into a Wb final state. The final state from the decay of a $t\bar{t}$ event will contain two b quark jets and, depending on whether the W bosons decay leptonically or hadronically, either two leptons, one lepton and two jets, or four jets. Either of the states containing leptons will also have missing transverse energy ($\not\!\!E_T$) from the unobserved neutrinos.

The l+track channel cross-section discussed in this analysis is a measurement of the dilepton $t\bar{t}$ final state. The dilepton final state is characterized by two high p_T leptons, two b quark jets, and large missing transverse energy. In the l+track channel, one and only one of the leptons is required to have been identified as an electron or muon and the second lepton is identified by an isolated track in the tracking system. Two possible channels are considered here: either an identified electron plus isolated track, or an identified muon with isolated track. The primary background in the e+track (μ+track) channel comes from $Z \to ee$ ($Z \to \mu\mu$) events with fake $\not\!\!E_T$. Physics backgrounds are diboson and $Z \to \tau\tau$, and there are also backgrounds from QCD jets faking either the identified lepton or the isolated track or both. A previous measurement based on a 370 pb^{-1} data set can be found in Ref. [4].

II. DATASET

The dataset used for this analysis is the full RunIIa dataset, which was collected from April 2002 to March 2006. The recorded luminosity for this dataset is 1036 pb^{-1} in the e+track channel and 994 pb^{-1} in the μ+track channel.

III. MONTE CARLO

The expected signal is estimated using MC $t\bar{t}$ events generated by the Alpgen event generator [5] which uses LO matrix elements. Events are then processed by Pythia [6] for fragmentation, hadronization, and short-lived particle decay.

The $Z \to ll$ backgrounds are also estimated using Alpgen with Pythia for fragmentation and hadronization. A K factor is calculated by normalizing the Monte Carlo to the data on a low $\not\!\!E_T$ sample. This K factor is shown in Tables I-II. The contribution from heavy flavor quark pairs (bb and cc) is considered separately.

	$Z \to ee$	$Z \to \tau\tau$	$t\bar{t}$	WW	WZ	ZZ	W+fake	QCD	Data	K_Z
1 jet	270.19	0.73	0.10	0.10	0.70	0.63	0.71	1.33	308	1.12
2 jet	78.53	0.24	0.39	0.02	1.30	1.31	0.58	0.43	88	1.07

TABLE I: Number of expected and observed events in the Z sample in e+track, used to calculate K_Z.

	$Z \to \mu\mu$	$Z \to \tau\tau$	$t\bar{t}$	WW	WZ	ZZ	W+fake	QCD	Data	K_Z
1 jet	308.22	0.84	0.11	0.09	0.89	0.77	0.55	0.18	324	1.04
2 jet	106.95	0.52	0.63	0.04	1.55	1.86	-0.09	0.04	131	1.18

TABLE II: Number of expected and observed events in the Z sample in μ+track, used to calculate K_Z.

The diboson backgrounds (WW, WZ, and ZZ) are simulated using Monte Carlo events produced by the Pythia event generator. Pythia is a leading order (LO) event generator, so the cross sections are normalized with a K factor to bring it up to the NLO cross section. The WW sample is normalized to the NLO cross-section of 12.0 pb, WZ sample is normalized to 3.68 pb, and ZZ to 1.42 pb. All cross sections quoted here are from Ref. [7]. The K-factor between LO and NLO is approximately 1.4, and we use a systematic uncertainty of ± 0.4 on this K factor.

IV. EVENT SELECTION

The trigger used in this analysis is a lepton+jets trigger, which requires one lepton with $p_T > 15$ GeV and a single jet with p_T of 20-30 GeV, depending on trigger version [8]. Events are required to have one identified lepton with

$p_T > 15$ GeV and $|\eta| < 1.1$ for electrons or $|\eta| < 2$ for muons. The lepton+track channel is used to identify events with one misreconstructed lepton by searching for an isolated track. In this analysis isolated tracks must have $p_T >$ 15 GeV and $|\eta| < 2$. Since this analysis is intended to be combined with the identified lepton channels (dielectron, electron-muon, and dimuon) [1], events with two or more identified leptons are vetoed. Due to a very slight mismatch in the muon definitions used, the μ+track analysis is not quite orthogonal to the dimuon analysis despite this veto. However, it has been checked that no data events are selected by both the dimuon and μ+track selections. Other than this one exception, all of the channels are orthogonal to each other.

All jets in this analysis must have $p_T > 20$ GeV and $|\eta| < 2.5$, and events are required to have at least one jet with a $p_T > 40$ GeV. This high p_T cut on the leading jet substantially reduces the background from the Z boson with only a few percent loss of the $t\bar{t}$ signal.

The neutrinos in dilepton top pair events gives these events a large missing transverse energy ($\not{E}_T$), which can be used to distinguish top pairs from Z boson events. Events in the e+track channel are required to have $\not{E}_T > 20$ GeV. This cut is raised to 25 GeV if the invariant mass of the track+electron system is inside the Z window, 70-110 GeV. In the μ+track channel the cut is $\not{E}_T > 25$ GeV or $\not{E}_T > 35$ GeV if the invariant mass of the track+muon system is inside the Z window. Furthermore, we have defined a new variable $\not{E}_T^{Z-fit}$ which is designed to reduce the fake $\not{E}_T$ in Z events by rescaling the track and lepton momenta to bring the invariant mass of the track+lepton system to the Z resonance (91.2 GeV), and then using these rescaled p_Ts to correct the $\not{E}_T$. The cuts on $\not{E}_T^{Z-fit}$ are 20 GeV (or 25 GeV in the Z window) in the e+track channel and 25 GeV (35 GeV in the Z window) in the μ+track channel.

Finally, the Z boson background is further reduced by requiring at least one jet to be identified as a jet originating from a b quark. One jet must pass a cut of 0.65 of the DØ Neural Net tagger [9]. Monte Carlo events are weighted according to the probability that they would pass this cut:

$$P = 1 - \prod_{i=1}^{Njets} (1 - \epsilon_i) \tag{1}$$

where ϵ_i is the probability for a jet to be identified as a b quark jet. The probability for a jet to be identified as a b quark jet is broken down into the "taggability", which is the efficiency for a jet to have tracks in the tracking system, and the "tag rate function", which is the efficiency for a taggable jet to be identified as a b jet. The overall efficiency is broken down into taggability times tag rate function in order to separate detector inefficiencies (taggability) from the algorithm's performance (tag rate function). The taggability of light parton jets is measured in data. Heavy flavor jets have greater track multiplicity and thus higher taggability, so the ratio of the taggability of heavy (b or c) jets to light flavor jets is estimated from Monte Carlo and verified on a data sample enriched in heavy flavor jets. The tag rate functions are measured with data using the System8 formalism, which constructs a system of 8 equations and 8 unknowns using two different algorithms and two data samples with different b quark content.

In this anaylsis, $t\bar{t}$ to dilepton events with two reconstructed jets are identified as having at least one of those jets from a b quark almost 70% of the time. This number falls to 50% if only one of the jets was reconstructed.

V. BACKGROUND ESTIMATION

The estimate for the background from fake leptons and/or tracks is made by solving a 4×4 matrix, as explained below. Here a "real track" is a track from a lepton and a "fake track" is a track from any other source. A track from a misidentified jet would still be called "fake" in this context. There are three possible sources of fake events which must be estimated:

- The identified lepton is real, but a QCD jet fakes the track ($N_{RL,FT}$).
- A QCD jet fakes the identified lepton, but the track comes from a real lepton ($N_{FL,RT}$).
- A QCD multijet event has a fake identified lepton and a fake track ($N_{FL,FT}$).

In the matrix method one defines a looser set of selection requirements on the identified lepton and the isolated track. Events selected with the loose selection requirements are enriched in background from QCD jets faking the lepton and/or track. In this analysis, loose objects are defined as follows:

- Loose electrons do not have any cut on an electron likelihood variable. This likelihood variable is designed to distinguish electrons from QCD jets.

- Loose muons do not have any calorimeter isolation or track isolation requirements.
- Loose tracks have a weaker track isolation requirement.

The loose lepton, loose track ($N_{LL,LT}$) sample has three subsamples created by tightening the lepton cut ($N_{TL,LT}$), the track cut ($N_{LL,TT}$) or both ($N_{TL,TT}$). The quantities $N_{RL,RT}$, $N_{RL,FT}$, $N_{FL,RT}$, and $N_{FL,FT}$ can then be estimated from $N_{LL,LT}$, $N_{TL,LT}$, $N_{LL,TT}$ and $N_{TL,TT}$ by inverting a 4×4 matrix which is a function of the efficiencies for real and fake leptons to pass the tight requirements.

VI. SYSTEMATICS

Jet Systematics: There are three sources of uncertainty from jets: jet energy calibration, jet energy resolution, and jet reconstruction efficiency. Jet energy calibration is a rescaling of the momentum of jets in both data and Monte Carlo that is used to correct the energy of jets back to the particle level. Jet energy resolution is an oversmearing of the jet momentum in Monte Carlo events to account for differences in the MC and data jet resolutions. The effect of jet reconstruction efficiency is simulated by randomly removing Monte Carlo jets according to the data to Monte Carlo scale factor. Jet energy scale and jet energy resolution systematics are evaluated by varying them within their uncertainties. The jet reconstruction efficiency uncertainty is estimated by varying the data to MC scale factor downward by 1 σ and then assuming the uncertainty is symmetric about the central value. Only the downward variation is used because an upward variation gives a scale factor bigger than one in some cases, which can not then be simulated by the above procedure of randomly removing jets. The uncertainties from jet systematics are fully correlated between the e+track and μ+track channels and between the 1 and 2 jet bins.

Lepton ID: Data to Monte Carlo scale factors must be applied to electrons, muons, and tracks in order to correct the efficiency for a Monte Carlo object to successfully pass all object identification cuts. Varying the electron scale factor within its uncertainty gives a systematic uncertainty on the e+track cross section and likewise the muon scale factor produces a systematic in the μ+track channel. Scale factor uncertainties from electron and muon scale factors are uncorrelated between e+track and μ+track channels but fully correlated between jet bins.

The track scale factors are a product of a track reconstruction scale factor, a quadratic p_T parametrization and a quartic η parametrization. There are four sets of parameters (all combinations of loose/tight and electron track/muon track scale factors). Each of these parameters is varied individually by $\pm 1\sigma$ and the resulting uncertainty is calculated on an event-by-event basis. The track scale factor uncertainty is fully correlated between channels and jet bins.

Opposite charge selection: The identified lepton and the isolated track are required to have opposite charge. The charge measurement is estimated to cause a 2% downward uncertainty. Although muon tracks are not expected to have as large an uncertainty as electron tracks, here we conservatively apply a 2% uncertainty to both the e+track and μ+track channels. This uncertainty is fully correlated between channels and jet multiplicity bins.

Data Quality: The systematic uncertainty on the measurement of the data quality efficiency is estimated to be 0.5%. This uncertainty is taken to be fully correlated between channels and jet multiplicity bins.

Vertex ID: The estimated uncertainty from the primary vertex identification is 3%. Additionally, there is an estimated 2.2% uncertainty due to differences between data and MC in the z vertex position. Vertex systematics are fully correlated between channels and jet mulitplicities.

Trigger Efficiencies: Monte Carlo events are weighted by the trigger efficiencies in order to reproduce the trigger selection. These efficiencies are p_T and η dependent. The systematic uncertainties from the trigger is estimated by varying the trigger efficiencies by $\pm$ 1 σ. The trigger efficiency systematic is uncorrelated between the e+track and μ+track channels but fully correlated between the 1 and 2 jet bins.

Normalization of Backgrounds: The normalization of the Z background is determined by normalizing the Monte Carlo to the data in a Z-dominated, low $\not\!\!E_T$ sample. Statistical uncertainties will give a systematic uncertainty on the cross section. We have also used the difference between the K factors calculated in the e+track and μ+track channels as an additional systematic.

The normalizations of the fake backgrounds (W+fakes and pure fakes) are determined by the Matrix Method. Statistical uncertainties on the samples $N_{LL,LT}$, $N_{TL,LT}$, $N_{LL,TT}$, $N_{TL,TT}$ gives a systematic uncertainty on the cross section. A second source of systematic uncertainty comes from the uncertainties on the measurement of the signal and background efficiencies. These uncertainties are fully uncorrelated between channels and jet multiplicities.

b Jet Identification: The systematic uncertainty due to b quark jet identification is evaluated by fluctuating within uncertainties the efficiencies for Monte Carlo jets to pass the b jet identification cut. This effficiency includes both the contribution from taggability and the tag rate functions (Section IV). b jet identification systematics are fully correlated between channels and jet multiplicities.

Luminosity: The uncertainty in the total integrated luminosity at DØ causes a systematic uncertainty in the cross-section measurement of 6.1% [10].

Luminosity Profile: MC events used in this analysis are generated with an overlay of zero bias events from data. The luminosity distribution of the zero bias events used for MC generation does not precisely match the actual luminosity distribution in data. To estimate the size of the effect from this, the MC was reweighted in order to match the MC luminosity profile to the data profile, and the difference between this reweighted profile and the unweighted MC was used as an additional systematic. Luminosity reweighting is only used for this systematic estimation.

Source	e+track		μ+track		combined	
	σ^- (pb)	σ^+ (pb)	σ^- (pb)	σ^+ (pb)	σ^- (pb)	σ^+ (pb)
Electron ID	-0.25	0.28			-0.16	0.16
Muon ID			-0.04	0.04	-0.01	0.02
Muon Track			-0.04	0.04	-0.01	0.02
Muon Isolation			-0.11	0.12	-0.05	0.05
Opp. Charge Sel.	0.00	0.10	0.00	0.11	0.00	0.10
Vertex ID	0.00	0.15	0.00	0.16	0.00	0.16
Vertex Z simulation	-0.10	0.11	-0.11	0.12	-0.11	0.11
Data Quality	-0.02	0.02	-0.03	0.03	-0.02	0.02
Jet Scale	-0.13	0.10	-0.10	0.17	-0.12	0.13
Jet Resolution	-0.02	0.00	0.00	0.00	-0.02	0.00
Jet ID	-0.02	0.02	-0.01	0.01	-0.02	0.02
TRFs / Taggability	-0.24	0.27	-0.28	0.32	-0.26	0.29
Track ID	-0.51	0.57	-0.71	0.80	-0.60	0.67
Trigger (e+jets)	-0.14	0.18			-0.08	0.11
Trigger (μ+jets)			-0.40	0.58	-0.17	0.23
MC Statistics	-0.07	0.07	-0.10	0.10	-0.06	0.06
K Factors	-0.24	0.31	-0.28	0.39	-0.18	0.30
Luminosity Profile	-0.20	0.20	-0.02	0.02	-0.11	0.11
Mat Meth ϵ Err.	-0.14	0.28	-0.18	0.29	-0.13	0.26
Mat. Meth. Statistics	-0.10	0.10	-0.12	0.12	-0.07	0.08
Total	-0.75	0.89	-0.96	1.20	-0.77	0.93

TABLE III: Table of systematic uncertainties in the e+track, μ+track, and combined channels.

VII. RESULT

The number of predicted and observed events used for the cross section measurement are shown in Table IV. The $t\bar{t}$ estimate assumes a cross section of 7 pb.

Sample	e+track, 1 jet	e+track, 2 jets	μ+track, 1 jet	μ+track, 2 jets
$t\bar{t}$	1.92	10.13	1.32	7.99
$Z \rightarrow ll$	0.90	0.85	0.95	1.18
$Z \rightarrow \tau\tau$	0.21	0.17	0.19	0.19
WW	0.05	0.03	0.04	0.03
WZ	0.01	0.02	0.01	0.02
ZZ	0.02	0.06	0.02	0.04
W+fake	0.14	0.48	0.10	-0.22
QCD	0.21	0.21	0.03	0.00
Total Predicted	3.52	11.99	2.72	9.32
Observed	4	8	1	8

TABLE IV: Number of predicted and observed events in the tagged sample. $t\bar{t}$ estimate based on a 7 pb cross section.

In order to maximize the sensitivity of the analysis and minimize the effects of systematic uncertainties, each channel (e+track and μ+track) and both jet multiplicity bins are used in the cross section analysis, resulting in four independent channels. The cross section is determined by maximizing the product of the likelihoods. The number of expected events in channel i is:

$$\tilde{N}_i = \sigma BR\mathcal{L}\epsilon_i + N_i^{bkg} \tag{2}$$

where σ is the desired $t\bar{t}$ cross section, BR is the branching fraction of $t\bar{t}$ events to dileptons, $\mathcal{L}$ is the luminosity, ϵ_i is the efficiency for $t\bar{t}$ events to pass the selection cuts and N_i^{bkg} is the number of expected background events. The likelihood is then the product of the Poisson distributions:

$$\mathscr{L}(\sigma, [N_i^{obs} N_i^{bkg}, BR, \mathcal{L}, \epsilon_i]) = \prod_{i=1}^{4} \frac{\tilde{N}_i^{N_i^{obs}}}{N_i^{obs}!} e^{-\tilde{N}_i} \tag{3}$$

Channel	Branching Ratio	Luminosity	$t\bar{t}$ selection eff
e+track, 1 jet	0.1066	1036 pb^{-1}	0.25%
e+track, 2 jet	0.1066	1036 pb^{-1}	1.31%
μ+track, 1 jet	0.1066	994 pb^{-1}	0.18%
μ+track, 2 jet	0.1066	994 pb^{-1}	1.08%

TABLE V: Inputs to the cross section calculation.

The cross sections for the individual and combined channels, derived with a $t\bar{t}$ MC set with top mass 175 GeV, are:

$$\text{e} + \text{track}: \quad \sigma = 4.7^{+2.2}_{-1.8}(stat)^{+0.9}_{-0.8}(syst) \pm 0.3(lumi)\, pb \tag{4}$$

$$\mu + \text{track}: \quad \sigma = 5.3{+}2.5_{-2.0}(stat)^{+1.2}_{-1.0}(syst) \pm 0.3(lumi)\, pb \tag{5}$$

$$\text{combined}: \quad \sigma = 5.0^{+1.6}_{-1.4}(stat)^{+0.9}_{-0.8}(syst) \pm 0.3(lumi)\, pb \tag{6}$$

The cross section of $t\bar{t}$ is strongly dependent on the mass of the top quark. The cross section has been evaluated with $t\bar{t}$ MC with a mass of 165, 175, and 185 GeV. A linear fit of these three points gives a mass dependence of the form

$$\sigma(M_{top}) = 13.13 - 0.04644 M_{top} \tag{7}$$

Evaluating this at the top quark world average mass of 170.9 GeV gives

$$\sigma(\mathrm{M_{top}} = 170.9\mathrm{GeV}) = 5.2^{+1.6}_{-1.4}(stat)^{+0.9}_{-0.8}(syst) \pm 0.3(lumi) \tag{8}$$

The cross section as a function of top mass is shown in Figure 1.

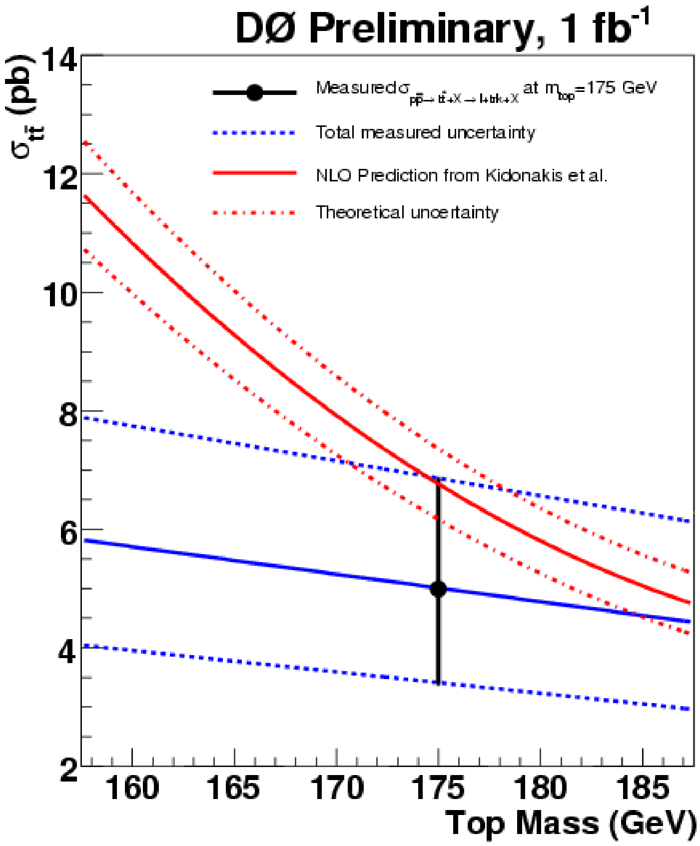

FIG. 1: Measured cross section vs. assumed mass of the top quark.

VIII. APPENDIX A: CONTROL PLOTS

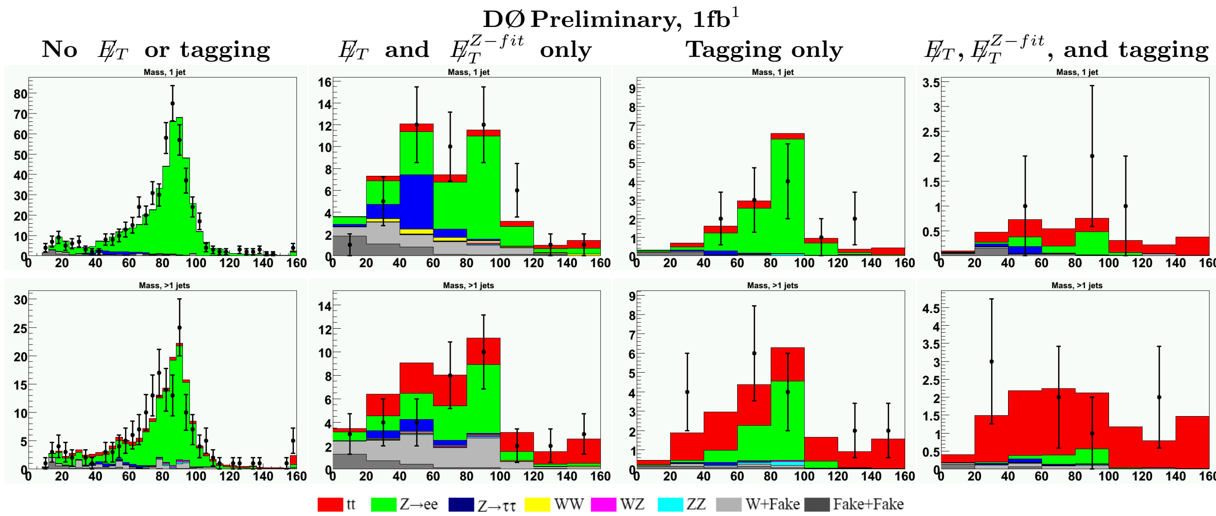

FIG. 2: Mass of electron-track pair in e+track. First row is the 1 jet exclusive bin, second row is 2 jet inclusive bin.

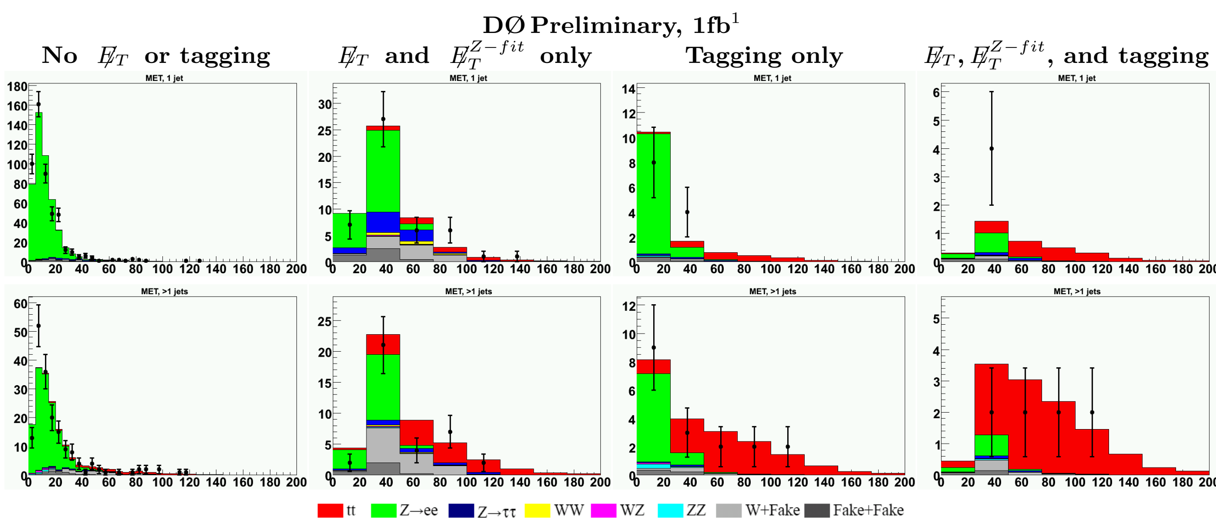

FIG. 3: $\not{E}_T$ in e+track. First row is the 1 jet exclusive bin, second row is 2 jet inclusive bin.

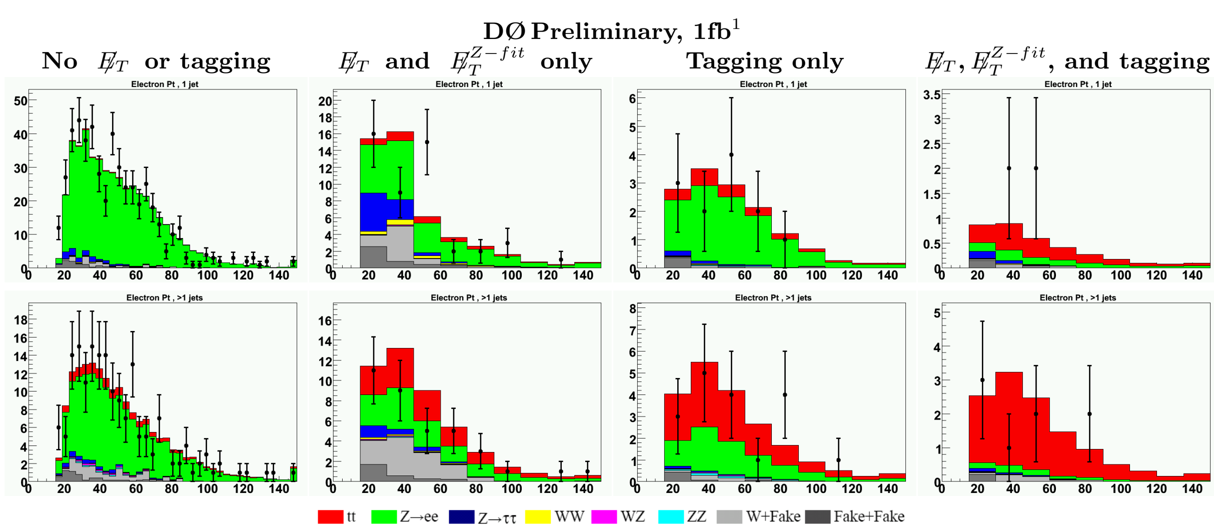

FIG. 4: Electron p_T in e+track. First row is the 1 jet exclusive bin, second row is 2 jet inclusive bin.

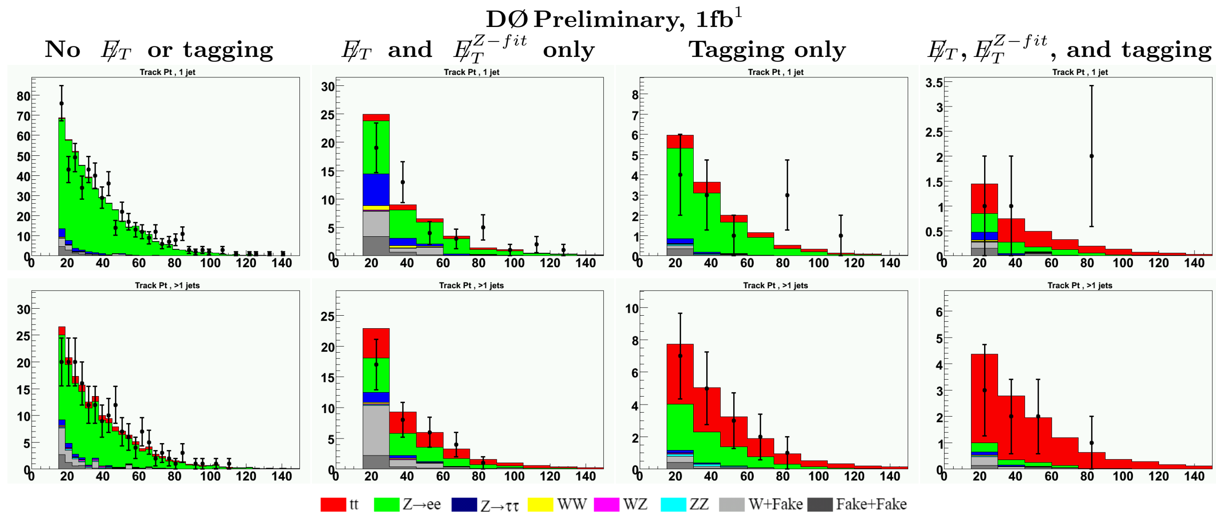

FIG. 5: Track p_T in e+track. First row is the 1 jet exclusive bin, second row is 2 jet inclusive bin.

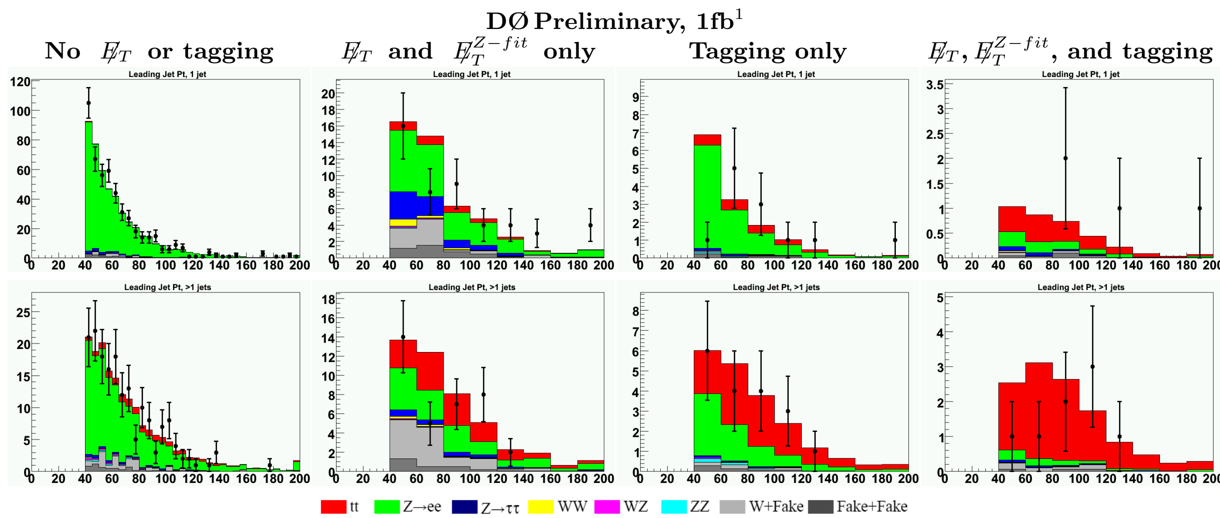

FIG. 6: Leading jet p_T in e+track. First row is the 1 jet exclusive bin, second row is 2 jet inclusive bin.

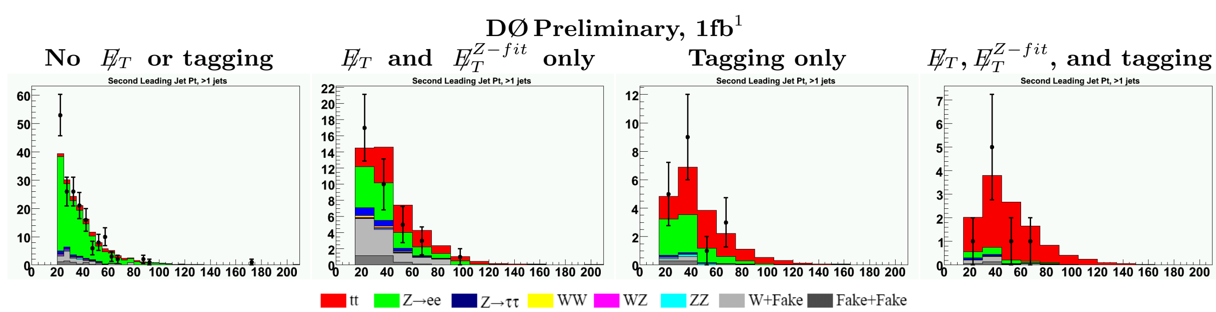

FIG. 7: Second leading jet p_T in e+track, 2 jet inclusive bin.

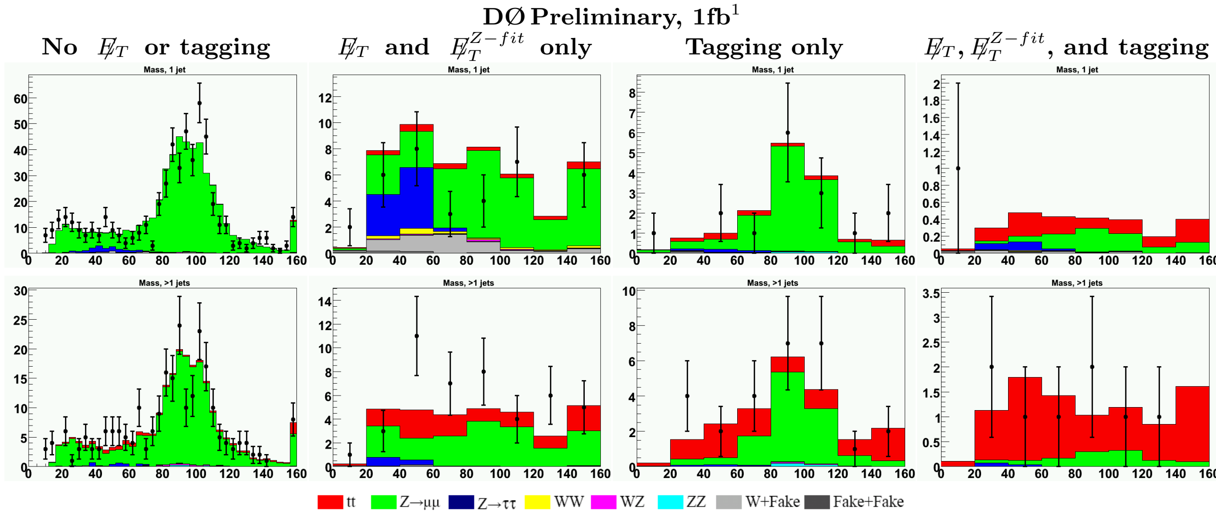

FIG. 8: Mass of muon-track pair in μ+track. First row is the 1 jet exclusive bin, second row is 2 jet inclusive bin.

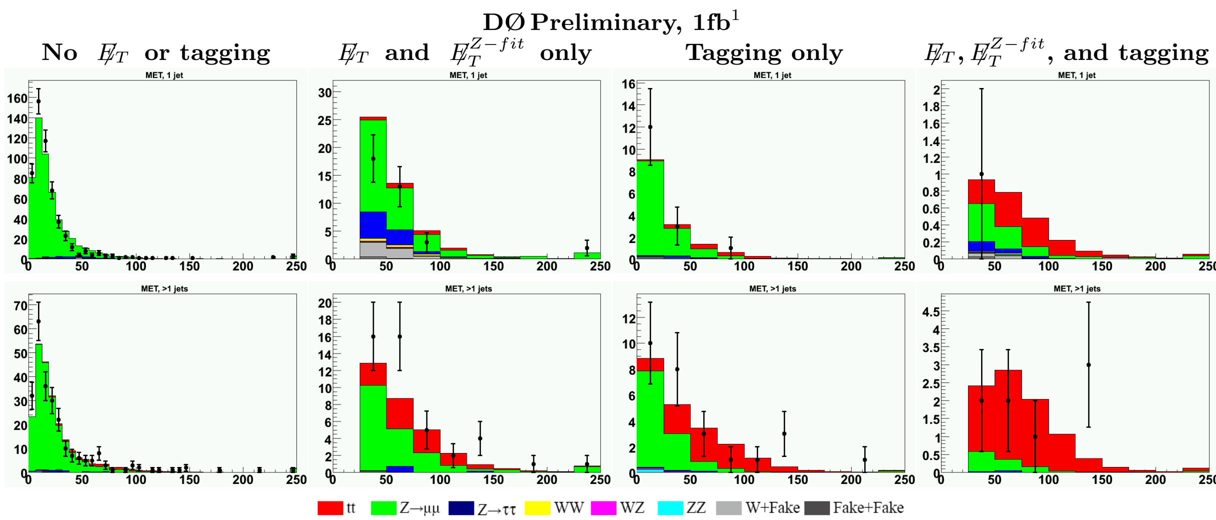

FIG. 9: $\not\!\!E_T$ in μ+track. First row is the 1 jet exclusive bin, second row is 2 jet inclusive bin.

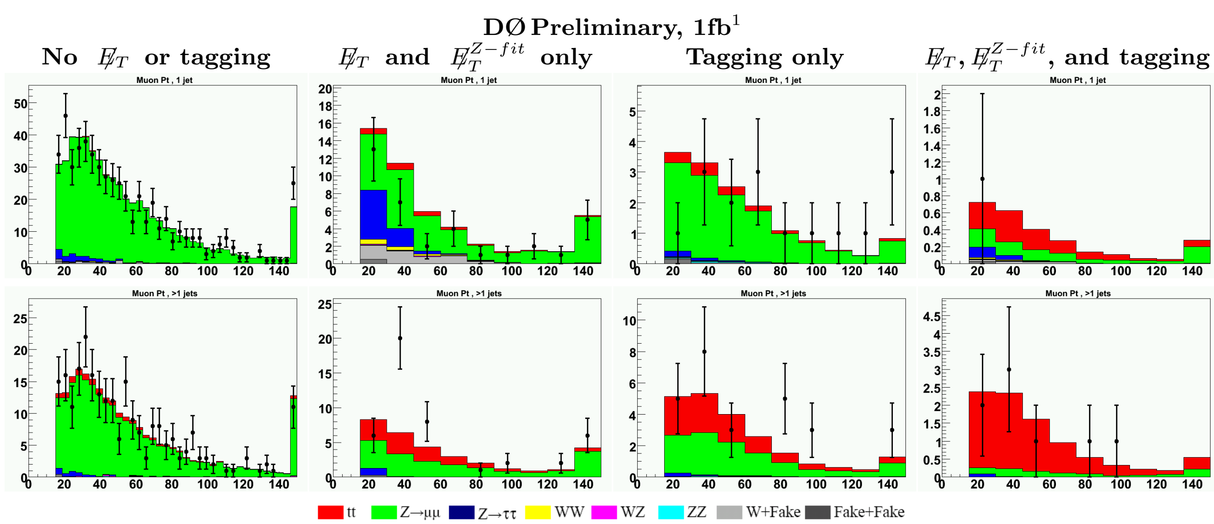

FIG. 10: Muon $\mathrm{p_T}$ in μ+track. First row is the 1 jet exclusive bin, second row is 2 jet inclusive bin.

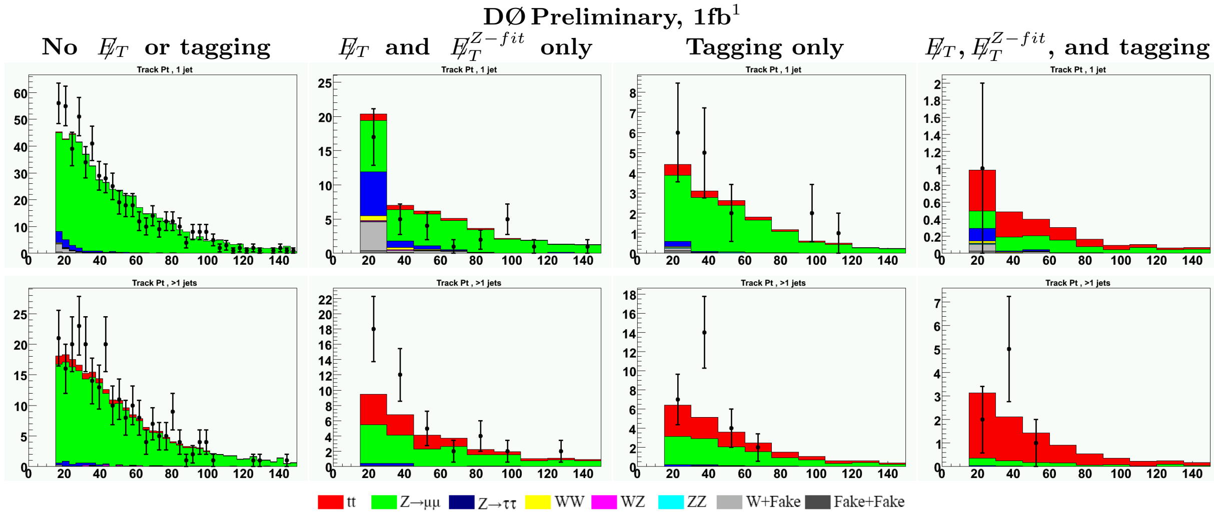

FIG. 11: Track p_T in μ+track. First row is the 1 jet exclusive bin, second row is 2 jet inclusive bin.

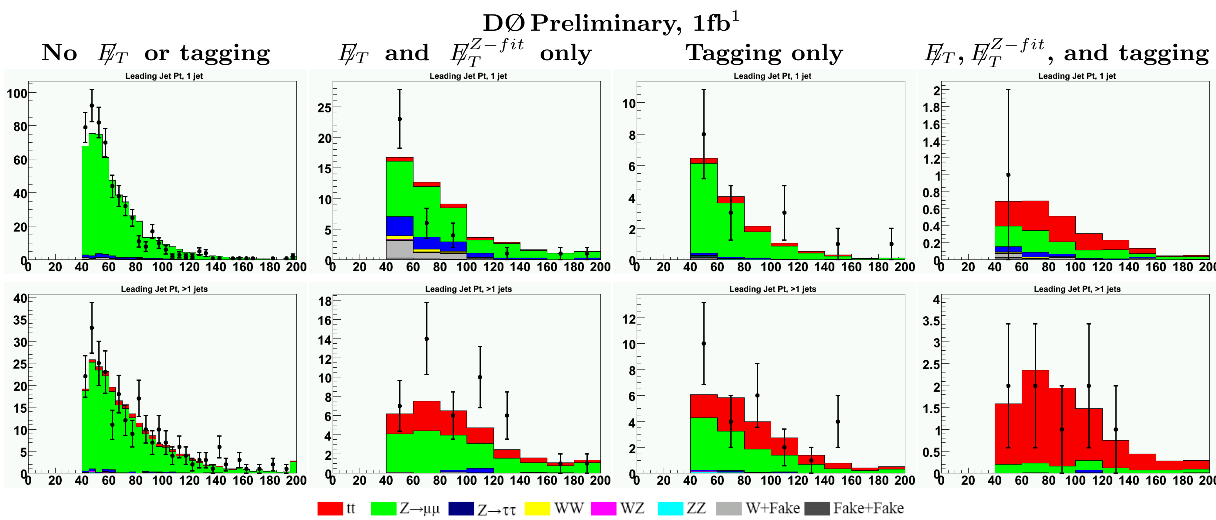

FIG. 12: Leading jet p_T in μ+track. First row is the 1 jet exclusive bin, second row is 2 jet inclusive bin.

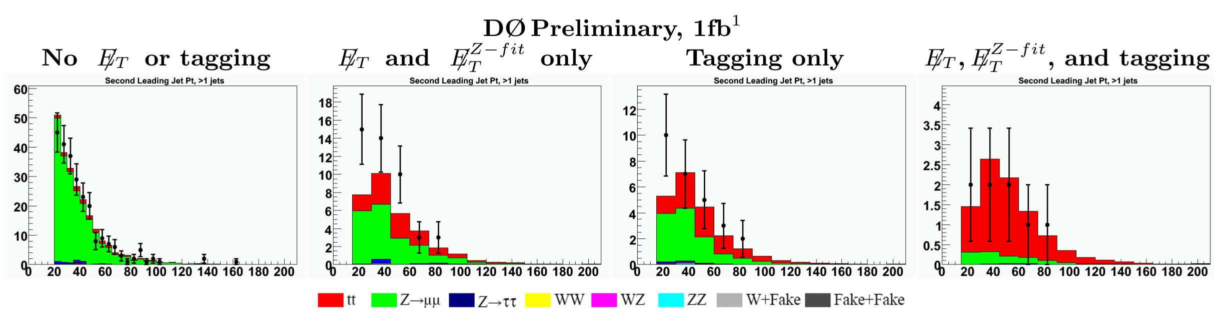

FIG. 13: Second leading jet p_T in μ+track, 2 jet inclusive bin.

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